The emplacement and crystallization of the U–Th–REE-rich agpaitic and hyperagpaitic lujavrites at Kvanefjeld, Ilímaussaq alkaline complex, South Greenland*

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The U–Th–REE deposit located at the Kvanefjeld plateau in the north-west corner of the Ilímaussaq alkaline complex, South Greenland, consists of lujavrites which are melanocratic agpaitic nepheline syenites. The fine-grained lujavrites of the Kvanefjeld plateau can be divided into a northern and a southern part with an intermediate zone between them. The northern part is situated along the north contact of the Ilímaussaq complex and continues east of the Kvanefjeld plateau as a lujavrite belt along the contact. This part has relatively 'low' contents of U, Th, and REE, and hyperagpaitic mineralogy is restricted to its highest-lying parts. The fine-grained lujavrites of the intermediate and southern part of the Kvanefjeld plateau occur between and below huge masses of country rocks which we show are practically *in situ* remnants of the roof of the lujavrite magma chamber. These lujavrites have high contents of U, Th, and REE, and hyperagpaitic varieties with naujakasite, steenstrupine and villiaumite are widespread.

We present a model for the formation of the fine-grained lujavrites of the Kvanefjeld plateau. In this model, an off-shoot from the large lujavrite magma body in the central part of the complex intruded into a fracture zone along the north contact of the Ilímaussaq complex and was forcefully emplaced from north-west to south-east. The intruding lujavrite magma was bounded to the west, north, and at its roof by strong volcanic country rocks, and to the south by the weaker, earlier rocks of the complex. The magma stored in the fracture crystallized, squeezing volatile and residual elements upwards. A subsequent violent explosion opened up fractures in the weaker southern rocks, and the residual volatile-enriched magma was squeezed into fractures in augite syenite, naujaite, and also in the overlying volcanic roof rocks. The removal of the volatile-rich lujavrite magma in the upper part of the fracture-bounded magma chamber made room for the rise of volatile-poor magma from the lower part of the magma chamber, and these lujavrites crystallized to form the northern continuous lujavrite belt.

Transfer and accumulation of volatile and residual elements in a lujavrite magma crystallizing below an impervious cover played a key role in the formation of the Kvanefjeld U–Th–REE deposit, as it also did in the crystallization of the lujavrite magma body in the central part of the Ilímaussaq complex.

Key words: Ilímaussaq, Kvanefjeld, U–Th–REE deposit, lujavrite, agpaitic, hyperagpaitic, steenstrupine, naujakasite, villiaumite, forceful emplacement.

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The Kvanefjeld plateau at the north-western corner of the Ilímaussaq* alkaline complex, South Greenland, has been a focus of economic interest since the discovery of its uranium–thorium deposit in 1956. Exploration was carried out by Danish Government institutions: the Geological Survey of Greenland, the Institute of Petrology of the University of Copenhagen, and the Atomic Energy Commission. The deposit was drilled in 1958, 1962, 1969 and 1977 with a total core length of 10,722 m. Core logs are described in internal reports by Sørensen *et al.* (1971), Nyegaard *et al.* (1977) and Nyegaard (1979).

The plateau was topographically mapped in 1957 and 1964, and geological mapping was carried out from 1964 to 1969 (Sørensen *et al.* 1969, 1974).

From 1978 to 1980, a 960 m long tunnel was driven through the Kvanefjeld lujavrites at an elevation of 470–512 m above sea level (a.s.l.), about 150 m below the surface of the plateau. Its geology is described in an internal report (Nyegaard 1980). The purpose was to procure material for ore beneficiation experiments, which were carried out at Risø National Laboratory, Denmark, and are documented in many reports (Kalvig 1983). The activities run by the Danish Government were closed in 1984 when nuclear energy was removed from the Danish agenda and uranium exploration was banned by the Greenland authorities.

In 2002, it was decided to close the research reactor at Risø and to clean the area of all radioactive materials. Because there was a great risk that the drill cores would be part of this decommissioning activity, we examined the cores once more to secure material of crucial geological importance. Representative samples from all cores are stored at the Department of Geography and Geology, University of Copenhagen.

Although the Danish exploration of the Kvanefjeld deposit was closed in 1984, scientific examination of the huge amount of sampled material has continued to this day. The present paper presents our interpretation of the emplacement and petrology of this unique mineral occurrence.

Geological setting

The Ilímaussaq complex (Fig. 1) is a late member of the Mid-Proterozoic Gardar province of South Greenland and dates to around 1160 Ma (see reviews by Larsen & Sørensen 1987; Markl *et al*. 2001; Sørensen 2006). It was intruded into basement granitoids and uncomformably overlying sandstones and lavas which form part of the Gardar supracrustals.

The complex is the type locality for agpaitic nepheline syenites (Ussing 1912), i.e. peralkaline nepheline syenites with complex Zr–Ti silicate minerals such as eudialyte and rinkite (the chemical compositions of the minerals mentioned in the text are given in Table 1). The term hyperagpaitic was introduced to characterize certain mineral associations in special pegmatites and veins from the Lovozero and Khibina complexes of the Kola Peninsula, Russia (Khomyakov 1995). These mineral associations represent a more highly evolved stage than in the common agpaitic rocks and are distinguished by a great variety of Na-rich minerals some of which are soluble in water. In the Ilímaussaq complex, hyperagpaitic mineral associations occur not only in pegmatites and veins but also in highly evolved lujavrites and in fenitized roof rocks (Sørensen 1997; Khomyakov *et al.* 2001; Sørensen & Larsen 2001; Andersen & Sørensen 2005).

The exposed part of the complex was emplaced in four main intrusive phases (Sørensen 2006). Phase 1 formed a mildly alkaline augite syenite shell, while phase 2 formed peralkaline quartz syenite and alkali

Table 1. Minerals mentioned in the text

Mineral	*Chemical formula*
aegirine	$NaFeSi_2O_6$
albite	$NaAlSi_3O_8$
analcime	$NaAlSi_2O_6{\cdot}H_2O$
arfvedsonite	$Na_3(Fe^{2+},Mg)_4Fe^{3+}Si_8O_{22}(OH)_2$
britholite	$(Ce,Ca)_5(SiO_4,PO_4)_3(OH,F)$
eudialyte	$Na_{15}Ca_6Fe_3Zr_3Si_{26}O_{73}(O,OH,H_2O)_3(Cl,OH)_2$
microcline	$KAlSi_3O_8$
monazite	$(Ce,La,Nd,Th)PO_4$
natrolite	$Na_2Si_3Al_2O_{10}{\cdot}2H_2O$
naujakasite	$Na_6(Fe,Mn)Al_4Si_8O_{26}$
nepheline	$(Na,K)AlSiO_4$
neptunite	$KNa_2Li(Fe,Mg,Mn)_2Ti_2Si_8O_{24}$
rhabdophane	$(Ce,La,Nd)PO_4{\cdot}H_2O$
rinkite	$(Na,Ca)_3(Ca,Ce)_4(Ti,Nb)(Si_2O_7)_2(O,F)_4$
Sodalite	$Na_4Si_3Al_3O_{12}Cl$
sphalerite	ZnS
steenstrupine	$Na_{14}(Ce,Th,U)_6Mn_2Fe_2Zr(PO_4)_7Si_{12}O_{36}(OH)_2{\cdot}3H_2O$
ussingite	$NaAlSi_3O_8NaOH$
villiaumite	NaF
vitusite	$Na_3(Ce,La,Nd)(PO_4)_2$
vuonnemite	$Na_5TiNb_3(Si_2O_7)_3O_2F_2{\cdot}2Na_3PO_4$

* old Greenlandic orthography is used for the established name of the geological complex; modern Greenlandic orthography is used for all place names.

granite sheets beneath the roof. Phase 3 formed a roof series which crystallized from the roof downwards in the succession pulaskite, foyaite, sodalite foyaite and the volumetrically dominant naujaite; the assumed simultaneously produced floor cumulates are not exposed. Phase 4 formed the exposed floor cumulates, kakortokites, followed upwards by varieties of aegirine lujavrite and arfvedsonite lujavrite. The lujavrites thus form a sandwich horizon between the roof series and the kakortokites (Ussing 1912; Ferguson 1964; Rose-Hansen & Sørensen 2002).

The Kvanefjeld plateau measures close to 2.1 x 0.9 km (Figs 1, 2) and comprises the westernmost part of a 4.5 km long belt of lujavrites that stretches south-west from the foothills of the Ilimmaasaq mountain (Fig. 1). The north and west margins of the plateau coincide with the north and west contacts of the complex. To the north-east the Kvanefjeld lujavrites are continuous with the lujavrites beneath Steenstrup Fjeld (Figs. 1, 3). The east margin of the plateau is the escarpment just east of the small peak of Kvanefjeld mountain (Fig. 3). The south-east margin is the steep slope towards the Narsaq Elv valley. In the western part of this slope, the lujavrites of the plateau are underlain by augite syenite and below that by naujaite. The eastern part of the valley slope consists from the top downwards of country rocks, medium- to coarse-grained lujavrite (M-C lujavrite), fine-grained lujavrite, and in the river valley naujaite (Fig. 4).

The adjacent country rocks are Gardar supracrustals - lavas, agglomerates and sandstones - which are intruded by dykes and sheets of gabbro and trachyte. These rocks form the NE–SW trending ridges that dominate the topography of the southern part of the plateau and are prominent in many of its drill cores, but they play a minor role in the northernmost part of the plateau and the area below Steenstrup Fjeld which are dominated by lujavrites (Figs. 1, 2; Sørensen *et al.* 1969, 1974; Nyegaard 1979).

The basaltic country rocks adjacent to the lujavrites below Steenstrup Fjeld and Ilimmaasaq mountain and in the ridges of gabbro and other roof rocks in the southern part of the Kvanefjeld plateau are strongly sheared. The vertical shear planes are oriented NE–SW, i.e. parallel to the contact of the complex. The shear zones in the ridges of roof rocks are intruded

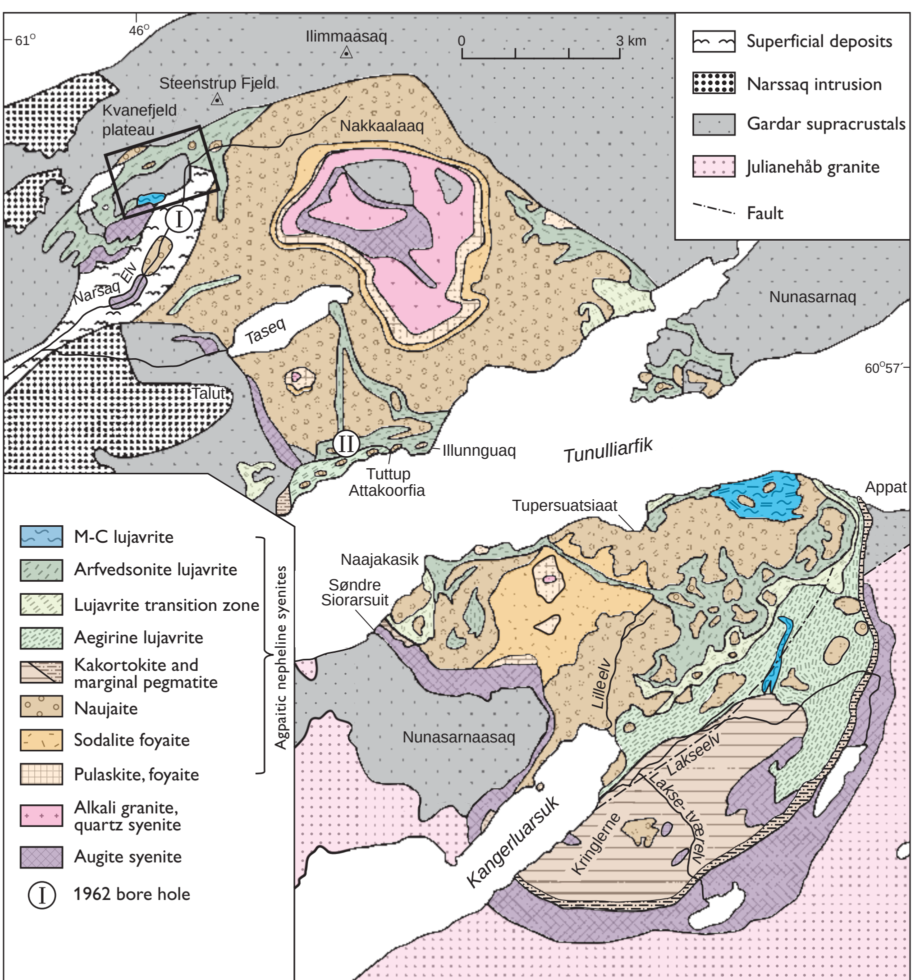


Fig. 1. Simplified geological map of the Ilímaussaq complex mainly based on Ferguson (1964) and Andersen *et al.* (1988). The frame in the upper left corner indicates the area shown in Fig. 2. Ringed numbers I and II are boreholes from 1962 mentioned in the text (Rose-Hansen & Sørensen 2002). All place names are given in modern Greenlandic orthography.

by fine-grained lujavrites (Sørensen *et al.* 1969, 1974).

Sørensen *et al.* (1974) divided the Kvanefjeld plateau into a southern central part, a northernmost part and a north-eastern part. We distinguish here a narrow northern part that is continuous with the lujavrites in the foothills of Steenstrup Fjeld and Ilimmaasaq mountain, a southern part dominated by the ridges of country rocks, and an intermediate zone between these two parts.

On the Kvanefjeld plateau and its south slope, lujavrites are exposed from 650 to 325 m a.s.l. (Sørensen *et al.* 1969) and in the steep foothills of Steenstrup Fjeld and Ilimmaasaq mountain from 800 to 400 m a.s.l. (Ferguson 1964; Sørensen 2006). Fine-grained lujavrites occur in most of the drill cores on the Kvanefjeld plateau, down to 195 m a.s.l. in core 37 terminating in naujaite, and down to 271 m a.s.l. in core 38 terminating in lujavrite. A borehole placed at a low stratigraphical position in the Kvanefjeld area and drilled to 500 m ended in lujavrite (GMEL 2008, p. 36).

In the northern part of the Kvanefjeld plateau, the lujavrites are separated from the country rocks by naujaite and a marginal pegmatite (Fig. 2) which are sheared and altered. Short apophyses of naujaite with the characteristic poikilitic texture intrude the basalts and there are small basaltic xenoliths in a narrow contact-near zone in the naujaite (Steenfelt 1972).

Naujaite xenoliths measuring tens of metres are seen on the surface and in drill cores from the plateau, the Steenstrup Fjeld area and at depth in the tunnel. Large augite syenite, alkali syenite and anorthosite xenoliths are restricted to the south-western part of the plateau where they dominate outcrops. Nielsen and Steenfelt (1979) noted the identical orientation of structures in some neighbouring augite syenite xenoliths.

Small (centimetre- to decimetre-sized) xenoliths of volcanic country rocks and naujaite are common in outcrops and cores. Xenoliths of pulaskite, foyaite and sodalite foyaite are found on the Kvanefjeld plateau and along the north contact of the complex from Kvanefjeld to Ilimmaasaq where some xenoliths consist of pulaskite and sheared basalt that may represent samples of the original apicalcontact of the complex. At Kvanefjeld, the transition from pulaskite to naujaite takes place over 5 m in one large roof series xenolith (Steenfelt 1972; Sørensen *et al.* 1974). In core 44 from the Steenstrup Fjeld area, centimetre- to decimetre-sized xenoliths change from foyaite through sodalite foyaite to naujaite with increasing depth and thus, despite fragmentation, reproduce the downward sequence of the roof series.

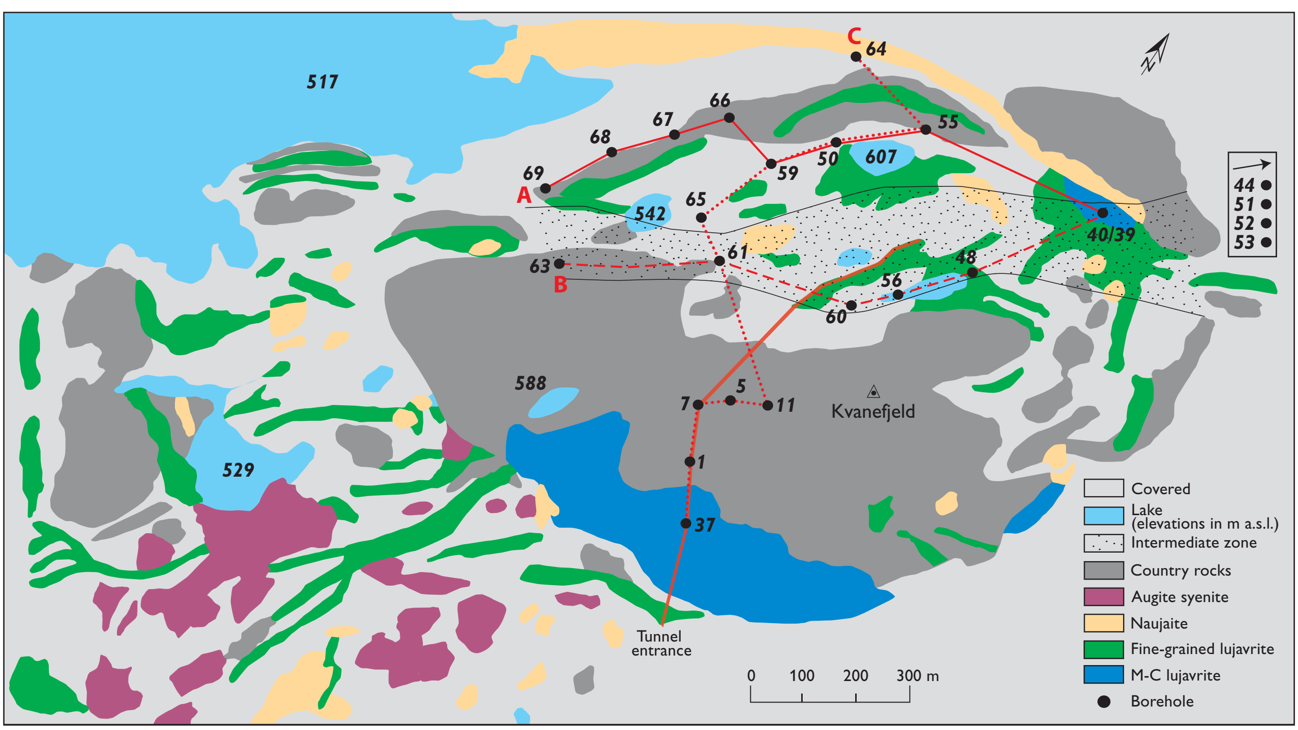


Fig. 2. Simplified geological map of the Kvanefjeld plateau based on Sørensen *et al.* (1974). Boreholes (drill cores) are shown as black dots with numbers. The kinked red lines A, B and C show the three constellations of drill cores depicted in Fig. 6. The location of all boreholes mentioned in the present paper is shown in Fig. 5. The position of the tunnel (thick red line) is shown projected onto the surface. The intermediate zone between the northern and southern parts of the Kvanefjeld plateau is discussed in the text.

Geological relations of the fine-grained lujavrites of the Kvanefjeld plateau

The Kvanefjeld plateau contains several varieties of fine-grained lujavrite including aegirine-, arfvedsonite-, naujakasite- and brown aegirine ('acmite') lujavrites. Because of the complexity of their distribution they are all grouped together as fine-grained lujavrite on the published geological map of the Kvanefjeld plateau (Sørensen *et al*. 1969, 1974). The M-C lujavrite in the southern part of the plateau represents a younger intrusive phase (Figs 2, 4) (Sørensen *et al*. 1969) and is not the subject of this paper.

Geological mapping of the northern part of the plateau showed a regular distribution of the different lujavrite types (Sørensen *et al*. 1974). The lujavrites in contact with the volcanic country rocks in the sidewall, and with the roof in cores 64 and 70, are rich in aegirine and grade inwards and downwards into arfvedsonite lujavrites. Aegirine lujavrite is found in contact with the naujaitic wall rocks, and aegirine commonly occurs in the contact between arfvedsonite lujavrite and naujaite xenoliths. The development of aegirine thus seems to take place near contacts.

The aegirine-rich lujavrites are succeeded inwards by arfvedsonite lujavrites and these again by lujavrites rich in brown aegirine (acmite in earlier literature), in the following called brown lujavrites, and by naujakasite lujavrites. Macroscopically, the northern arfvedsonite lujavrites are characterized by vertical sequences extending for around 100 m in drill cores and consisting of alternations of lujavrite with spheroidal texture and lujavrite with brown aegirine patches and schlieren (*cf.* Sørensen *et al*. 2003). It appears that there is a gradual transition from the lujavrites of the northern part of the plateau into those of the intermediate zone, often in the form of alternating bands of the different rocks. Rare cases of naujakasite lujavrite intruding other lujavrites have been noted, and there are at least two generations of naujakasite lujavrite. Exposures and the drill cores available to us are insufficient to decide whether the relations between these lujavrites and the lujavrites covered by gabbro in the southern part of the plateau are gradational or not.

Villiaumite is common in the cores at the Kvanefjeld plateau but, due to dissolution by groundwater, the cores lack villiaumite within 50 m of the surface and the mineral is uncommon down to the 100 m level. Villiaumite is rare elsewhere in the Ilímaussaq complex (Sørensen *et al.* 1974; Rose-Hansen & Sørensen 2002).

Naujakasite lujavrite

Naujakasite lujavrite occurs at several levels in the cores. It is the predominant lujavrite in the tunnel and has been observed in 28 of our 66 cores, although many of our cores are too shallow to reach the naujakasite lujavrite sequences (Fig. 5).

Naujakasite lujavrite typically occurs as the uppermost part of arfvedsonite lujavrite sequences. With the exception of cores 35, 50 and 56, which are located on naujakasite lujavrite exposures, and thin horizons in arfvedsonite lujavrite, naujakasite lujavrite in all cores examined by us underlies xenoliths of naujaite, augite syenite or country rocks. The highest-lying naujakasite lujavrites are in contact with the rocks of the roof of the lujavrite magma. At 580 to about 550 m a.s.l., naujakasite lujavrite underlies naujaite xenoliths, and at about 500 m a.s.l. it underlies augite syenite xenoliths. In eleven cores, there is a thin naujakasite-free zone between xenoliths and the underlying naujakasite lujavrite.

The majority of upper boundaries of naujakasite lujavrite horizons lie at 570 ± 10 m, 550 ± 10 m and 510 ± 10 m, a few at higher and lower elevations. Thin sheets of arfvedsonite lujavrite and naujakasite lujavrite intersect xenoliths of country rocks and naujaite at these el-

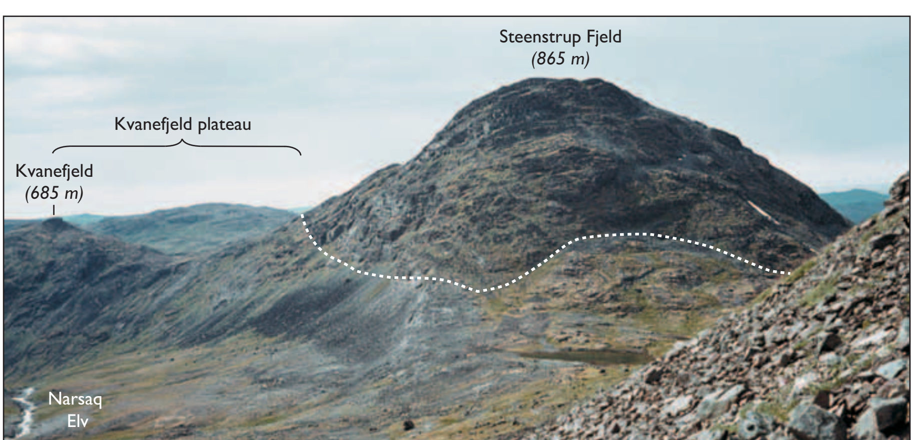


Fig. 3. The Kvanefjeld plateau seen between Steenstrup Fjeld to the right and Kvanefjeld to the left, looking WSW from the foothill of the Ilimmaasaq mountain. The sharp contact between the volcanic country rocks (right) and the scree-covered lujavrites is marked by a dashed white line.

evations, an indication of prominent near-horizontal fracture systems. Five cores terminate in naujakasite lujavrite. The longest naujakasite lujavrite intersection in cores is 95 m and the lowest-lying naujakasite lujavrite horizon is at 420 m a.s.l. Only exceptionally are naujakasite lujavrite horizons found at the same elevation in adjacent cores, though the elevation of their upper boundaries may vary in a regular way.

The 960 m long tunnel presents a horizontal N–S section through the plateau about 150 m below its surface (Figs. 2, 4). From its opening in the south slope of the plateau and northwards, the tunnel intersects augite syenite intruded by arfvedsonite lujavrite, a sheet of M-C lujavrite, and, measured from the opening, at 220–460 m, 585–640 m, 680–740 m and 755–880 m, four sections of naujakasite lujavrite which are separated from each other by sections of country rocks, naujaite and arfvedsonite lujavrite (Nyegaard 1980). The tunnel terminates in volcanic country rocks about 200 m from the position of the north contact, assuming that the contact plane is vertical. Thus naujakasite lujavrite dominates a more than 600 m wide horizon about 150 m below the surface of the plateau.

Of the many boreholes in the area above the tunnel, only boreholes 1 and 7 are intersected by the tunnel. In core 1, 20 m of naujakasite lujavrite forms the upper part of an arfvedsonite lujavrite sequence that terminates the core at 442 m a.s.l. (Fig. 6). In core 7, 95 m of naujakasite lujavrite terminate the core at 490 m a.s.l. (Fig. 6). There are three 10 m thick horizons of arfvedsonite lujavrite in the naujakasite lujavrite. Boreholes 1 and 7 are located about 125 m from each other. The upper boundary of the naujakasite lujavrite lies at 500 m a.s.l. in core 1, and at 585 m a.s.l. in core 7. This large difference of 85 m shows that the naujakasite lujavrite sections intersected by the tunnel cannot be assembled into one unbroken horizon. This impression is strengthened by the observation that cores 43 and 63, located about 200 m and 350 m west of the tunnel, intersect naujakasite lujavrite from 520 to 500 m a.s.l. in core 43 and from 500 to 430 m a.s.l in core 63, that is thicknesses of 20 and 70 m. Core 33 located 100 m west of core 7 has two horizons of naujakasite lujavrite at 570 to 560 and 518 to 505 m a.s.l., and in core 42, 50 m north of core 5, a 170 m long sequence of volcanic country rocks is intruded by naujakasite lujavrite from 610 to 555 and 515 to 495 m a.s.l. The few other long cores in this part of the plateau do not intersect naujakasite lujavrite.

Naujakasite lujavrite is absent in most cores from the north Kvanefjeld–Steenstrup Fjeld lujavrite belt, but it has been observed in outcrops and in cores 39, 50, 69 and 70. In core 50 it occurs as a thin zone in the uppermost part of an exposure of arfvedsonite lujavrite (Fig. 6), and in cores 39, 69 and 70 it occurs beneath country rock xenoliths in arfvedsonite lujavrite.

Borehole 35 is the most south-westerly borehole on the Kvanefjeld plateau, and here naujakasite lujavrite veins intrude the closely packed augite syenite and naujaite xenoliths. These veins have xenoliths of au-

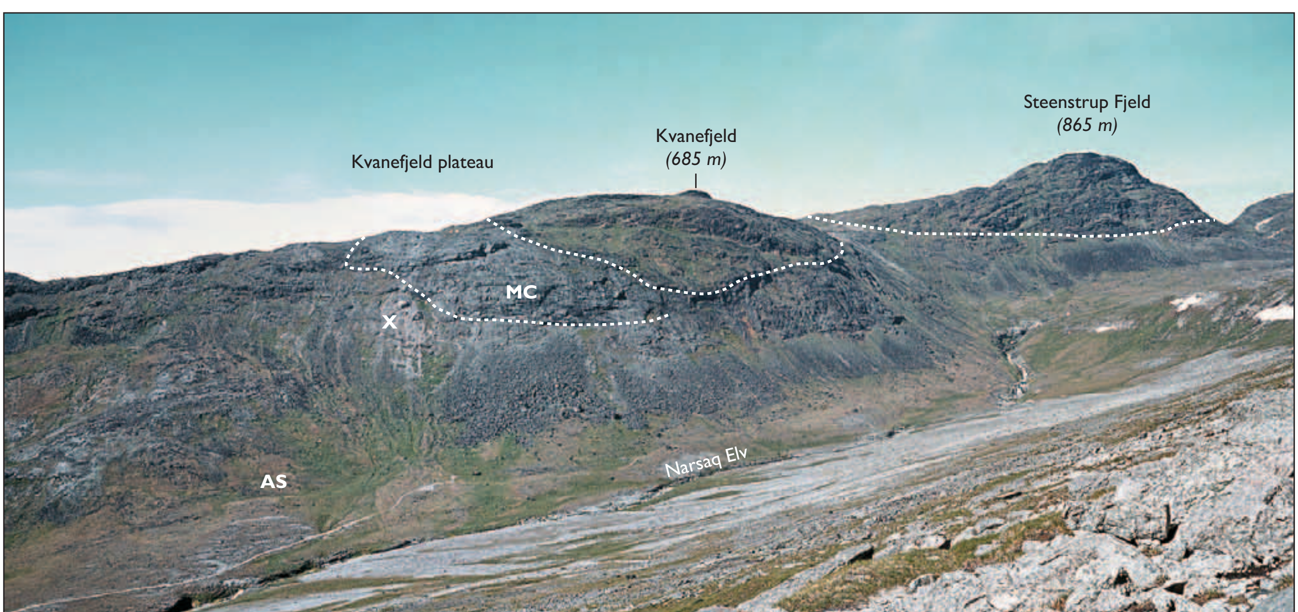


Fig. 4. Kvanefjeld with a small peak at 685 m in the centre and Steenstrup Fjeld to the right, viewed from the south. The sharp contact between the volcanic country rocks and the underlying lujavrites is marked by a dashed white line. In the centre of the photo, the medium- to coarse-grained lujavrite (MC) sheet underlying the volcanic rocks is also indicated. The brownish rock at the foot of the Kvanefjeld plateau to the left is augite syenite (AS). The light-coloured rock low in the river valley is naujaite. The photo is from 1974 before the tunnel was made. The entrance of the later tunnel is indicated with a white ×.

gite syenite, naujaite, foyaite and volcanic roof rocks. Parts of the south slope of the plateau are covered with veritable naujakasite gravel.

Steenstrup Fjeld lujavrites

The Steenstrup Fjeld lujavrites are continuous with the Kvanefjeld lujavrites (Figs. 1, 3, 4). The lujavrites in the footwalls of Steenstrup Fjeld and Ilimmaasaq mountain were not included in the detailed mapping of the Kvanefjeld plateau. A reconnaissance examination of the area and four boreholes (44, 51, 52, 53; Figs. 2, 6) showed that, similar to the northern part of the Kvanefjeld plateau, arfvedsonite lujavrite and brown lujavrite dominate this lujavrite area. The former is weakly radioactive (0.1–0.2 milliroentgen per hour (mr/h), similar to the northern arfvedsonite lujavrites of the plateau), whereas the brown lujavrite, in places naujakasite-bearing, is moderately radioactive (0.4-0.5 mr/h similar to the brown lujavrites of the plateau). Two samples of the brown lujavrite were analysed and contain 340 ppm U, 866 ppm Th, and 616 ppm U, 1560 ppm Th. The south contact of the lujavrites has been eroded but field relations indicate that naujaite formed the south wall (Fig. 1).

The arfvedsonite lujavrite next to the volcanic country rocks in the north contact is rich in aegirine and aegirine-bearing M-C lujavrite veins. A separate large body of aegirine lujavrite is enclosed in and intruded by the arfvedsonite lujavrite. Its lamination is near vertical and parallel to the lamination of the

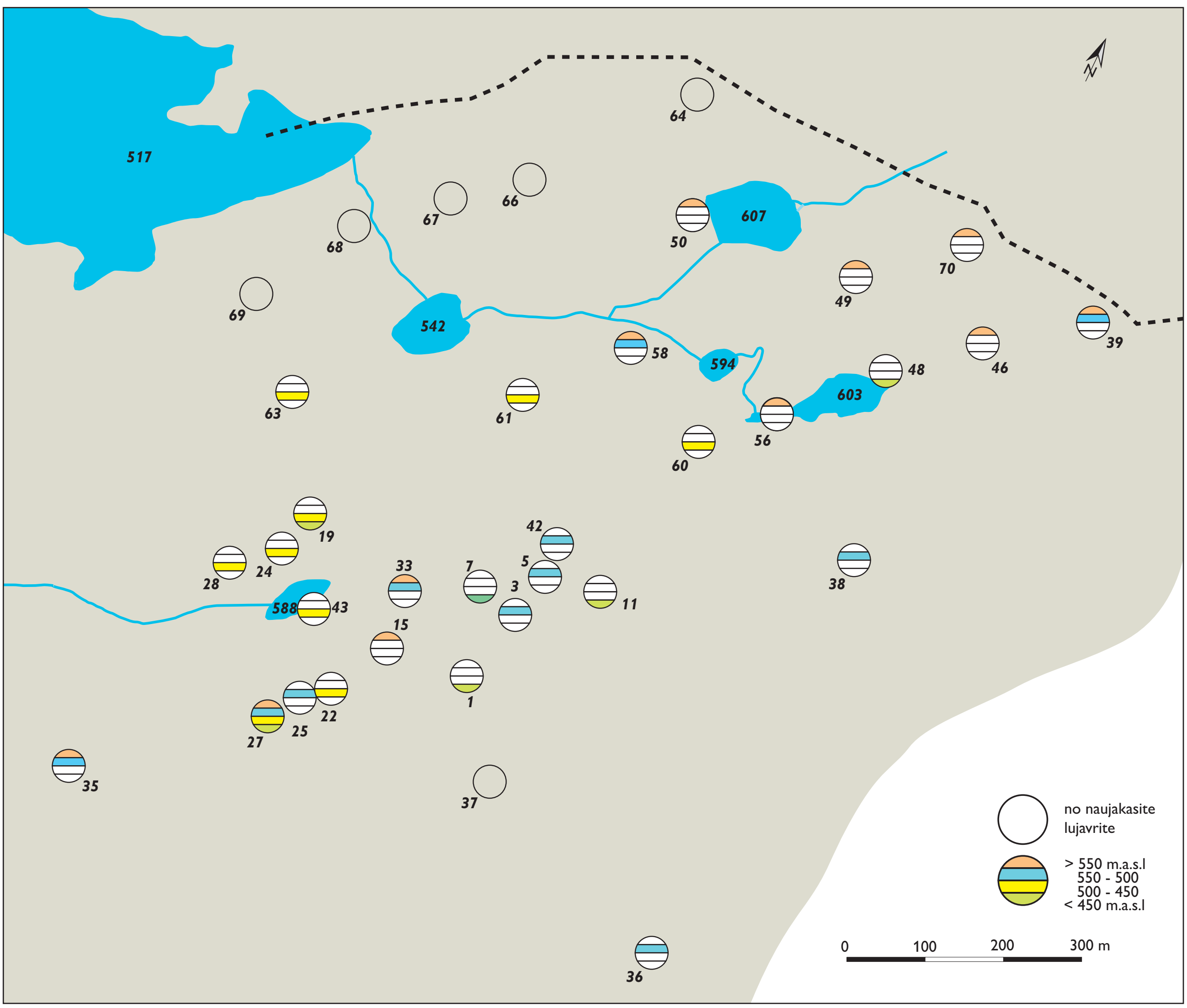
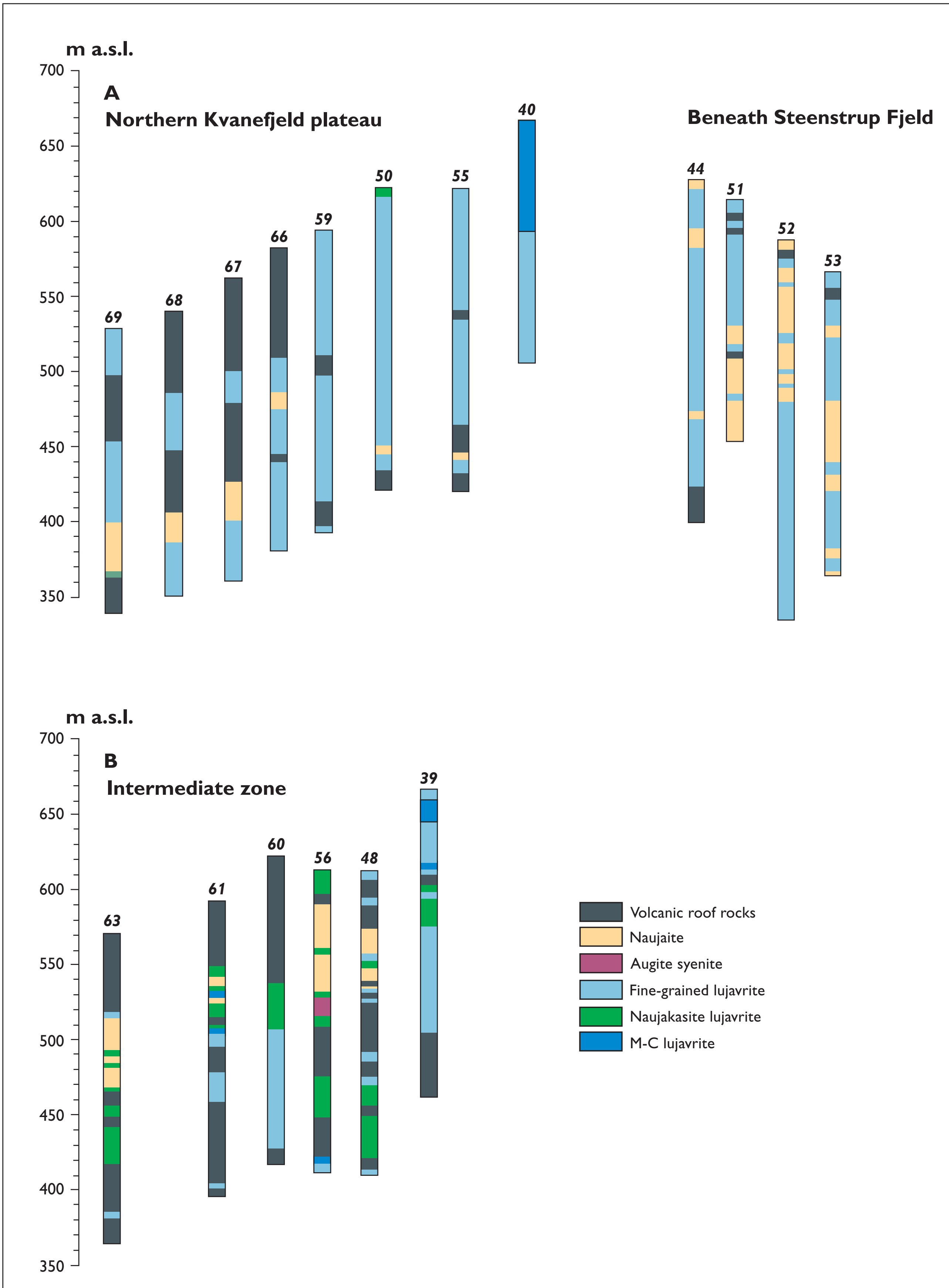


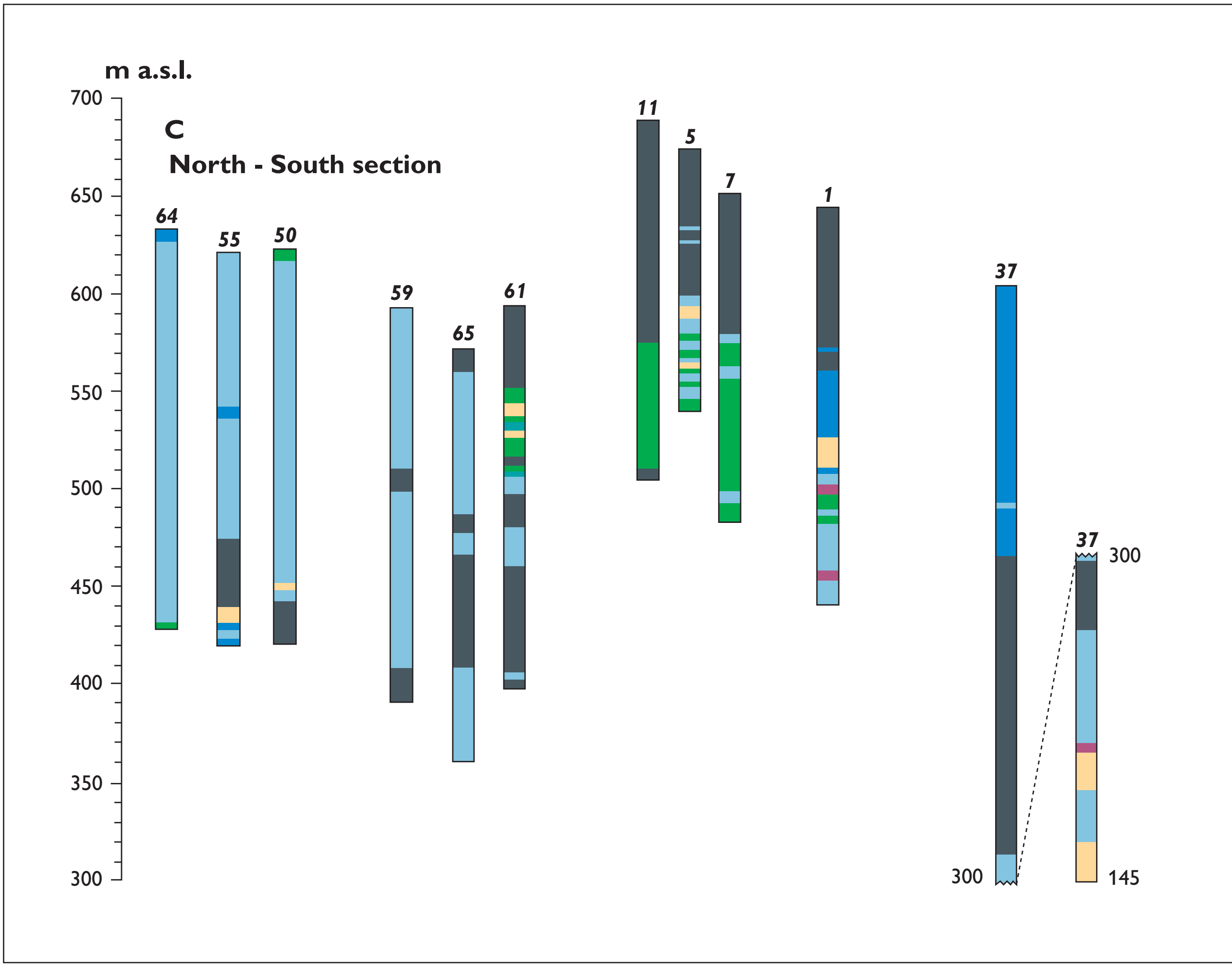
Fig. 5. Sketch map of the Kvanefjeld plateau showing the elevation of the upper boundary of the horizons of naujakasite lujavrite in the drill cores. The elevation is generally highest in the north-east and is lower and irregular in other parts of the plateau; see text for discussion. Compare with Fig. 2. The figure also shows the location of all the boreholes on the Kvanefjeld plateau mentioned in the text. The dashed line marks the north-eastern boundary of the Ilìmaussaq complex.



m a.s.l.
700
650
600
550
500
450
400
350
A
Northern Kvanefjeld plateau
Beneath Steenstrup Fjeld
69
68
67
66
59
50
55
40
44
51
52
53
m a.s.l.
700
650
600
550
500
450
400
350
B
Intermediate zone
63
61
60
56
48
39
Volcanic roof rocks
Naujaite
Augite syenite
Fine-grained lujavrite
Naujakasite lujavrite
M-C lujavrite

enclosing arfvedsonite lujavrite and to shear zones in the adjacent country rocks. Some sections of the cores consist of layered and /or spheroidal lujavrites. Large naujaite xenoliths are found in the upper parts of the two northerly cores (44 and 52), and in the lower part of the southerly cores (51 and 53; Fig. 6). Villiaumite is present in large parts of the lujavrites and also in naujaite. Naujakasite was not observed in the four cores. Small xenoliths of volcanic country rocks are widespread; xenoliths of pulaskite, foyaite, sodalite foyaite and augite syenite are found up to 770 m a.s.l. in the footwall of Ilimmaasaq mountain.

The area has been re-examined by Greenland Minerals and Energy Ltd. (GMEL) who found a 250 m wide zone of mineralized lujavrite at a higher level than represented by our four boreholes (GMEL 2008, p. 26).



◀ ▲ Fig. 6. Constellations of drill core logs. Facing page: **A**. Logs from the northernmost part of the Kvanefjeld plateau and the Steenstrup Fjeld area. With the exception of core 50, these cores do not contain naujakasite lujavrite. Note the sloping boundaries of xenoliths in cores 66-67-68-69 and of naujaite in cores 67-68-69. Also note that the number of roof rock xenoliths decreases from core 69 (west) to core 40 (east). **B**. Logs of cores from the southern part of the Kvanefjeld plateau where lujavrites crystallized under a tight cover of roof rocks and naujakasite lujavrite is frequent. Note the irregular location of naujakasite lujavrite in these cores, the possible arch-form of the elevation of the lower boundaries of roof xenoliths in cores 60-61-62-63, and that the roof xenoliths have been removed by erosion in cores 56-48-39. This page: **C**. A north-south section through the plateau. Cores 64-55-50-59-65 belong to the northern part of the plateau where naujakasite lujavrite is nearly absent. Cores 61-11-5-7-1 are from the central and southern part of the plateau where lujavrites crystallized under a tight cover and naujakasite lujavrite is frequent. Cores 1 and 7 intersect the tunnel at 500 m a.s.l. The lower boundary of the roof xenoliths in cores 11-5-7 forms an upwards-convex form and these cores have particularly thick naujakasite lujavrite sequences. Core 37 is the southernmost deep drill-hole that was sited in M-C lujavrite. Vertical scale, metres above sea level; horizontally, the cores are arranged with approximately correct distances between them. The location of the three sections A, B and C is shown in Fig. 2.

The M-C lujavrite

A large body of medium- to coarse-grained, unlaminated lujavrite, described as M-C lujavrite (Sørensen *et al.* 1969), is exposed in the south part of the Kvanefjeld plateau (Figs. 2, 4). It is at least 700 m long, roughly 200 m across and up to 160 m thick. It continues from the surface of the plateau at 610–620 m down through the tunnel at *c.* 480 m a.s.l. and is still present in some cores at 400 m a.s.l. It forms a cylinder- or sheet-like intrusion plunging towards the east. The M-C lujavrite intersects and encloses all other rocks and intersects the structures of the pre-existing intrusion breccia and its matrix of fine-grained lujavrite. It sends apophyses and pegmatitic and hydrothermal veins into the adjacent rocks which are strongly deformed, even folded, and are recrystallized and metasomatized up to 200 m from the contact of the body (Sørensen *et al.* 1969, 1974). In the contact aureole, gabbro and basalt with shear zones invaded by fine-grained arfvedsonite lujavrite are folded and recrystallized close to the M-C lujavrite. The result is a lujavrite-looking rock which, however, is a contact metamorphosed rock that cannot be distinguished from altered lujavrite in thin section. The arfvedsonite and feldspar are partly or wholly converted to aegirine and zeolites, respectively. These rocks are the U- and Th-richest rocks of the plateau with up to 15 vol. % steenstrupine that occurs in clusters of small crystals or as large crystals that may contain abundant inclusions and show a sub-poikilitic texture. The metasomatized rocks have up to 0.1% U and 0.5% Th and were the target for the first phase of uranium exploration.

Petrography of the lujavrites of the Kvanefjeld plateau

Away from the north contact, the aegirine lujavrite is moderately laminated and consists of nepheline wrapped by aegirine needles, microcline laths, pale yellow platy eudialyte and occasional albite laths. There is a small amount of sodalite. All felsic phases are partly altered to analcime, which also occurs interstitially. Aegirine can be surrounded by sub-poikilitic arfvedsonite and is occasionally altered to brown aegirine. Accessory minerals include vitusite, neptunite and sphalerite.

The Kvanefjeld plateau arfvedsonite lujavrites are strongly to moderately laminated, cumulate rocks. Subhedral crystals of nepheline and occasional sodalite are wrapped by smaller albite laths and/or microcline plates and stout prismatic arfvedsonite crystals. Nepheline and sodalite contain randomly

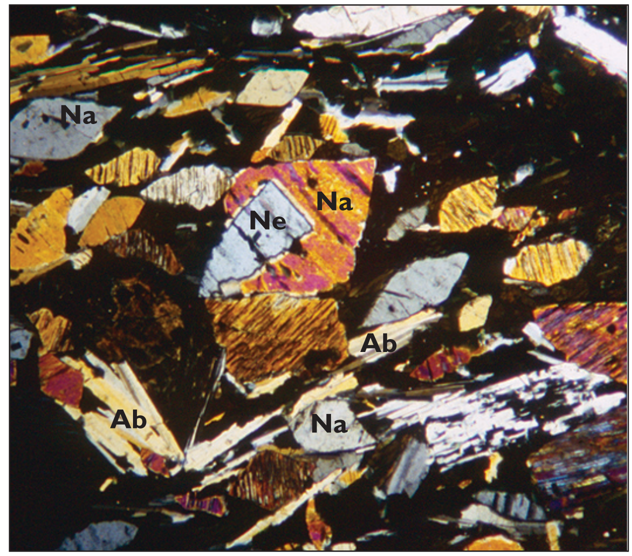


Fig. 7. Microphoto (crossed polarizers) of naujakasite lujavrite from core 7, depth 112.20 m. Note the parallel orientation of the lozenge-shaped naujakasite crystals (Na) and the feldspar laths (Ab). In the centre, a nepheline crystal (Ne) is partially overgrown by naujakasite. Black: arfvedsonite and analcime). Width of photo 5 mm.

oriented inclusions of arfvedsonite and feldspars. The albite laths are occasionally bent and broken. The microcline shows the tiled pattern of penetration twinning typical of agpaitic rocks (Ussing 1893; Sørensen 1962; Borutskii & Semenov 1969; Smith & McLaren 1983). Small platy, dusty eudialyte crystals are occasionally preserved and may reach *c.* 5 vol % but are usually altered to fine-grained mixtures of monazite splinters and other secondary products. Steenstrupine is widespread in the lujavrites of the southern and intermediate zones and may make up 10–15 vol. % of the rocks. Minor accessories include vitusite, britholite, white mica (?Li-mica), sphalerite, galena and monazite-rhabdophane pseudomorphs after vitusite. Ussingite occurs in millimetre-sized patches in a few thin sections of arfvedsonite lujavrite from the northern Kvanefjeld plateau where it replaces feldspars (Makovicky *et al.* 1980).

The distribution and varieties of steenstrupine overlap in naujakasite lujavrite and in the preceding and succeeding arfvedsonite lujavrite. The freshest steenstrupine is cream-coloured and metamict. Crystals are often zoned in shades of brown and variably altered to a fine-grained mixture of minerals. Small steenstrupine crystals tend to concentrate in the margins of naujakasite crystals (Buchwald & Sørensen 1961; Sørensen 1962; Wollenberg 1971; Sørensen *et al.* 1974; Makovicky *et al.* 1980; Khomyakov *et al.* 2001; Khomyakov & Sørensen 2001). Pseudomorphs after steenstrupine consist of monazite, neptunite and micron-sized thorite, but only of analcime and minute needles of arfvedsonite and aegirine in the ultimate alteration product.

Petrographically, when arfvedsonite lujavrite grades into naujakasite lujavrite, naujakasite appears to take over the role of nepheline. Grains of naujakasite can overgrow nepheline and there are examples of naujakasite with small, corroded nepheline cores (Fig. 7) (Khomyakov *et al*. 2001).

At all contents of naujakasite, the least altered rocks contain no well-defined interstitial material. Instead, there are isolated pools and patches of dusty natrolite or analcime.

Naujakasite lujavrite is overlain by arfvedsonite lujavrites in several drill cores. As the amount of naujakasite decreases, nepheline again becomes abundant. The arfvedsonite lujavrite overlying naujakasite

Table 2. Uranium and thorium in fine-grained lujavrites of the Kvanefjeld plateau

Tunnel	Distance from opening, m		Rock type*	U, ppm	Th, ppm	Th/U
	220–450		Njk lujavrite	296–603	402–1392	1.1–2.9
	585–640		Njk lujavrite	322–379	776–1126	2.2–2.4
	690–730		Njk lujavrite	192–330	245–876	2.3–2.4
	755–880		Njk lujavrite	298–543	654–1291	1.4–2.9
Boreholes	Depth in core, m	Zone				
No 1	147.60	S	Njk lujavrite	342	815	2.4
	156.06		Njk lujavrite	343	1100	3.2
	159.60		Arf lujavrite	470	1130	2.4
	178.50		Arf lujavrite	34	1340	3.8
No 5	82.52	S	Arf lujavrite	447	2495	5.6
	105.70		Arf lujavrite	271	613	2.3
	115.68		Arf lujavrite	464	1276	2.8
	124.40		Njk lujavrite	646	1671	2.6
No 7	81.05	S	Njk lujavrite	433	1352	3.1
	85.10		Njk lujavrite	483	1542	3.2
	91.50		Njk lujavrite	736	2165	2.9
	94.53		Njk lujavrite	825	3310	4.0
	106.50		Njk lujavrite	852	2875	3.4
	129.85		Njk lujavrite	639	1420	2.3
	145.70		Njk lujavrite	291	547	1.9
	161.10		Njk lujavrite	268	538	2.0
No 11	121.05	S	Njk lujavrite	531	1420	2.7
	130.25		Njk lujavrite	570	1185	2.1
	135.15		Njk lujavrite	263	790	3.0
	149.00		Njk lujavrite	462	650	1.4
	149.10		Njk lujavrite	410	700	1.7
	151.53		Njk lujavrite	403	1407	3.5
No 37	44.35	S	Arf lujavrite	317	743	2.3
No 38	382.50	S	Arf lujavrite	211	294	1.4
No 48	170	I	Njk lujavrite	376	874	2.3
No 49	74	I	Njk lujavrite	369	764	2.1
	120		Arf lujavrite	417	780	1.9
No 50	71	N	Arf lujavrite	280	360	1.3
No 55	40	N	Arf lujavrite	316	533	1.7
No 59	60	N	Arf lujavrite	243	619	2.6
No 60	101	N	Njk lujavrite	375	960	2.6
No 64	10	N	Ae lujavrite	106	186	1.8
No 70	140	N	Arf lujavrite	300	365	1.2

*) Ae= aegirine; Arf= arfvedsonite; Njk= naujakasite.
S = Southern Zone, I = Intermediate Zone, N = Northern Zone.

lujavrite is, in most cases, moderately to intensely zeolitized.

Solution cavities in the lujavrites are thought to indicate the former presence of villiaumite. This is clear for cavities where relict villiaumite is still present, but cavities may result from the former presence of other water-soluble minerals such as natrosilite (Sørensen 1982). There are occasional diffuse bands, as well as sharply defined veins, rich in villiaumite or relict cavities. In some villiaumite-bearing lujavrites, zeolites are totally or largely absent and only villiaumite occupies interstitial areas. Villiaumite is occasionally seen in metasomatized naujaite xenoliths (e.g. Nyegaard 1980). The interstitial distribution of villiaumite suggests it is a late magmatic mineral, and the occurrence of marginal zones of zeolites around cores of villiaumite imply that it is the last magmatic mineral to crystallize. In some rocks villiaumite forms large interstitial pools with poikilitic outer margins.

Geochemistry

For the fine-grained lujavrites of the Kvanefjeld plateau, the most comprehensive geochemical survey has been carried out for U and Th (examples in Table 2). This has been supported by analyses of characteristic elements from drill core samples in northern Kvanefjeld (Kunzendorf *et al.* 1982) and by major and trace element analyses of the main lujavrite types (Table 3). The U and Th contents were determined by gamma-spectrometry as described by Løvborg *et al.* (1968, 1971, 1972, 1980). Major and trace element analyses were performed by X-ray fluorescence analysis, following the methods described in Kystol and Larsen (1999) and Bailey *et al.* (2006).

From the north contact to the central and southern parts of the plateau, the U contents of the lujavrites increase from 130–140 to 310–320 ppm U, Th from 90–200 to 360–390 ppm, and Th/U ratios from *c.* 1 to *c.* 2 (Nyegaard 1979).

Sheets of fine-grained steenstrupine arfvedsonite lujavrite accompanied by mineralizations containing steenstrupine, Li-mica, sphalerite, Be-minerals and monazite occur in fractures in the volcanic country rocks. These lujavrites have 400–800 ppm U and Th/U ratios of 2–4 (and up to 8) (Sørensen *et. al.* (1974, p. 35).

In the tunnel, the two innermost naujakasite lujavrite sequences have U contents varying from 192 to 543 ppm, Th from 245 to 1291 ppm and Th/U ratios from 1.4 to 2.9 (Table 2). In the two outermost naujakasite lujavrite sequences, U varies from 296 to 603 ppm, Th from 402 to 1392 ppm and Th/U from 1.4 to 2.4 (Nyegaard 1980). The average values for

Table 3 Chemical analyses of fine-grained lujavrites from the Kvanefjeld plateau

	1	2	3
Core	55	55	48
Depth(m)	162.59	69.60	163.00
Major elements (wt%)			
SiO_2	51.22	48.25	50.02
TiO_2	0.24	0.25	0.22
ZrO_2	0.75	0.45	0.16
Al_2O_3	12.06	12.30	13.12
Fe_2O_3	5.44	7.03	4.27
FeO	8.80	7.72	9.40
MnO	0.56	0.54	0.70
MgO	0.06	0.02	0.03
CaO	0.26	0.14	0.19
Na_2O	9.90	14.31	12.41
K_2O	3.31	3.41	3.28
P_2O_5	0.73	0.58	0.48
H_2O^+	3.41	1.78	1.94
H_2O^-	0.09	0.09	0.07
F	0.04	1.04	0.48
Cl	0.09	0.37	0.18
S	0.15	0.16	0.21
others	1.57	1.00	1.68
sum	98.59	99.44	98.29
A.I.	1.65	2.21	1.83
FeO*	13.69	14.04	13.24
ns	7.48	11.92	10.35
Zr/U	58.6	17.0	3.2
Trace elements (ppm)			
Nb	480	275	428
Y	595	671	929
Th	76	89	970
U	95	196	358
Ba	75	29	32
La	3210	2060	2490
Ce	3900	2350	3460
Nd	937	529	899
Li	741	792	882
Be	48	39	61
Sr	46	30	33
Rb	557	936	971
Zn	2680	1430	2450
Pb	466	332	346
Ga	101	115	131
As	1.6	8.3	6.8
Br	<0.5	1.9	2.9
Mo	1.1	12	18
Ge	2.0	1.9	1.8
Tl	2.5	3.4	3.1
Cs	12	8.6	30
Sn	248	514	317

1. arfvedsonite lujavrite, 2 villiaumite-arfvedsonite lujavrite, 3 naujakasite lujavrite. A.I., agpaitic index; FeO*, total iron as FeO; ns, normative sodium disilicate.

the four naujakasite lujavrite sequences from the opening inward are: U 419, 348, 304 and 440 ppm; Th 726, 911, 597 and 1051 ppm; Th/U 1.2, 2.6, 1.9 and 2.4. Thus, in the two innermost sequences, U contents are relatively constant and lower than in the two outermost sequences, whereas Th contents are more variable. This recalls the relations observed in drill cores where U contents vary very little with elevation in long sequences of naujakasite lujavrite but decrease abruptly when approaching the overlying xenolith. Th contents and Th/U ratios are more variable and generally increase abruptly at the top of the naujakasite lujavrite sequences.

U contents, however, increase upwards in the 200 m long cores near the north contact that are dominated by arfvedsonite lujavrite and locally by aegirine lujavrite. In sequences where arfvedsonite lujavrites are overlain by naujakasite lujavrites, U contents generally increase upwards in arfvedsonite lujavrite but remain more or less constant in the naujakasite lujavrite. Th contents and Th/U ratios may be more or less parallel to the U contents in the arfvedsonite lujavrite, but generally increase upwards in the naujakasite lujavrite sequences, as mentioned above. There are also cases where U contents decrease upwards, or first increase and then decrease. Th and Th/U may follow the same pattern or increase upwards.

The general increase in U and Th contents towards the higher levels in lujavrites coincides with an upward decrease in Zr contents in the lower part of the lujavrite sequence (Kunzendorf *et al.* 1982). The combination of relatively low U-Th and high Zr is characteristic for arfvedsonite lujavrite containing eudialyte, whereas high U-Th combined with low Zr is characteristic for naujakasite lujavrite where eudialyte is absent but steenstrupine is significantly present (Andersen *et al.* 1981a; Kunzendorf *et al.* 1982).

The highest U content recorded by us is 1.70 wt% U that was found in a hydrothermal mineralization in the contact between the arfvedsonite lujavrite and the overlying roof of volcanic rocks in the foothill of the Ilimmaasaq mountain in the easternmost part of the lujavrite belt (Rose-Hansen *et al.* 1977).

Multi-element analyses of three lujavrite samples (Table 3) are consistent with these variations in U-Th versus Zr. The most striking difference between the arfvedsonite lujavrite and naujakasite lujavrite is the high Na_2O in the latter which is responsible for the high agpaitic index and normative *ns* (sodium disilicate) (*cf.* Sørensen 1997; Khomyakov *et al.* 2001). The mineral chemistry of naujakasite translates to *ns* = 12 wt. %. Naujakasite lujavrite is also characterized by a high content of MnO (Table 3).

Fluorine and Na_2O contents increase from the arfvedsonite lujavrite to naujakasite lujavrite (Table 3) and are clearly linked to the presence of villiaumite. Increased levels of villiaumite lead to an increased agpaitic index and *ns* (an increase of 4 wt. % villiaumite increases *ns* by *c.* 6 wt %). The abundance of villiaumite in both arfvedsonite lujavrite and naujakasite lujavrite is erratic, despite its well-established interstitial setting.

The content of P_2O_5 reflects the presence of REE phosphates and REE silicophosphates such as vitusite, monazite, and especially steenstrupine. The abundance of REE + Y varies from around 9,000 to 15,000 ppm.

In general, the fine-grained lujavrites at the Kvanefjeld plateau have high contents of many residual elements (U, Th, REE, Y, P, F, Li, Be, Rb, Cs, Sn, Zn, Pb, Mo, As, Tl, Ga).

Discussion

Lujavrite thickness

In the northernmost part of the Kvanefjeld plateau, a narrow zone of arfvedsonite lujavrite is delineated by our 200 m long drill cores (Fig. 6a, c). Most of our boreholes in the southern part of the complex are too shallow to estimate the thickness of the lujavrites underlying the large roof rock xenoliths. Thus, we have only an incomplete knowledge of the architecture of these lujavrites, i.e. how much space there is between xenoliths and how these are oriented. There are indications of more than 100 m thick lujavrite sequences but no definitive information about their lateral extent.

According to GMEL (2008, 2009), the lujavrite forms thick sub-horizontal layers that are continuous for hundreds of metres. Their sections indicate that the thick layers are split up into several thin layers towards the southwest.

Emplacement of the fine-grained Kvanefjeld lujavrites and relations to earlier rocks

The fine-grained lujavrites of the central part of the Ilímaussaq complex are sandwiched between naujaite and kakortokite and were emplaced after these rocks had solidified. At the time of the formation of the central sandwich lujavrites, the upper part of the complex consisted of a huge naujaite dome draped over by a package of sodalite foyaite, foyaite and pulaskite from the third intrusive phase, augite syenite from the first phase and alkali granite from the second phase, and at the apical part of the dome at Nakkaalaaq by remnants of the roof of volcanic rocks (Fig. 1).

Protrusions from the lujavrite sandwich horizon transgress the naujaite and are in direct contact with the country rocks along parts of the east and west contacts of the complex (Fig. 1). We interpret the NE–SW-oriented lujavrite belt from Ilimmaasaq mountain to the Kvanefjeld plateau in the northwest corner of the complex as a protrusion along the north contact of the complex.

In the north wall of the Narsaq Elv valley, naujaite is in contact with the country rocks from about 1000 m a.s.l. below Ilimmaasaq mountain to 800 m a.s.l. From 800 to 600 m a.s.l., the lujavrite belt forms the contact without disturbing its regular course, i.e. the emplacement of the lujavrite was controlled by the wall of country rocks in the north contact of the naujaite. The basaltic country rocks are strongly sheared parallel to the contact, an indication that the lujavrite was emplaced through a fracture system along the north contact of the complex.

The lujavrite belt sends a south-directed 'finger' into the naujaite south of Steenstrup Fjeld, and three lujavrite 'fingers' penetrate the southwest contact of the complex (Fig. 1), indicating a forceful SW-directed emplacement of the lujavrite magma.

At 600 m a.s.l. the lujavrite belt becomes the northernmost part of the Kvanefjeld plateau and is separated from the country rocks by a narrow zone of naujaite and marginal pegmatite that forms a bulge on the north contact of the complex (Figs 1, 2). Naujaite apophyses intrude the country rocks proving that the naujaite is located in its place of consolidation. The logical explanation of the isolated occurrence is that this naujaite is the contact facies of a larger naujaite body that occupied the area before the emplacement of the lujavrite. The bulge was separated from the main naujaite body when the lujavrite magma intruded into fractures in the shear zone along the north contact and engulfed the naujaite adjacent to the shear zone. The occurrence of large naujaite xenoliths on the Kvanefjeld plateau and in the Steenstrup Fjeld area, and in drill cores from these two areas, proves that a large body of naujaite occupied the Kvanefjeld area when the lujavrite was emplaced.

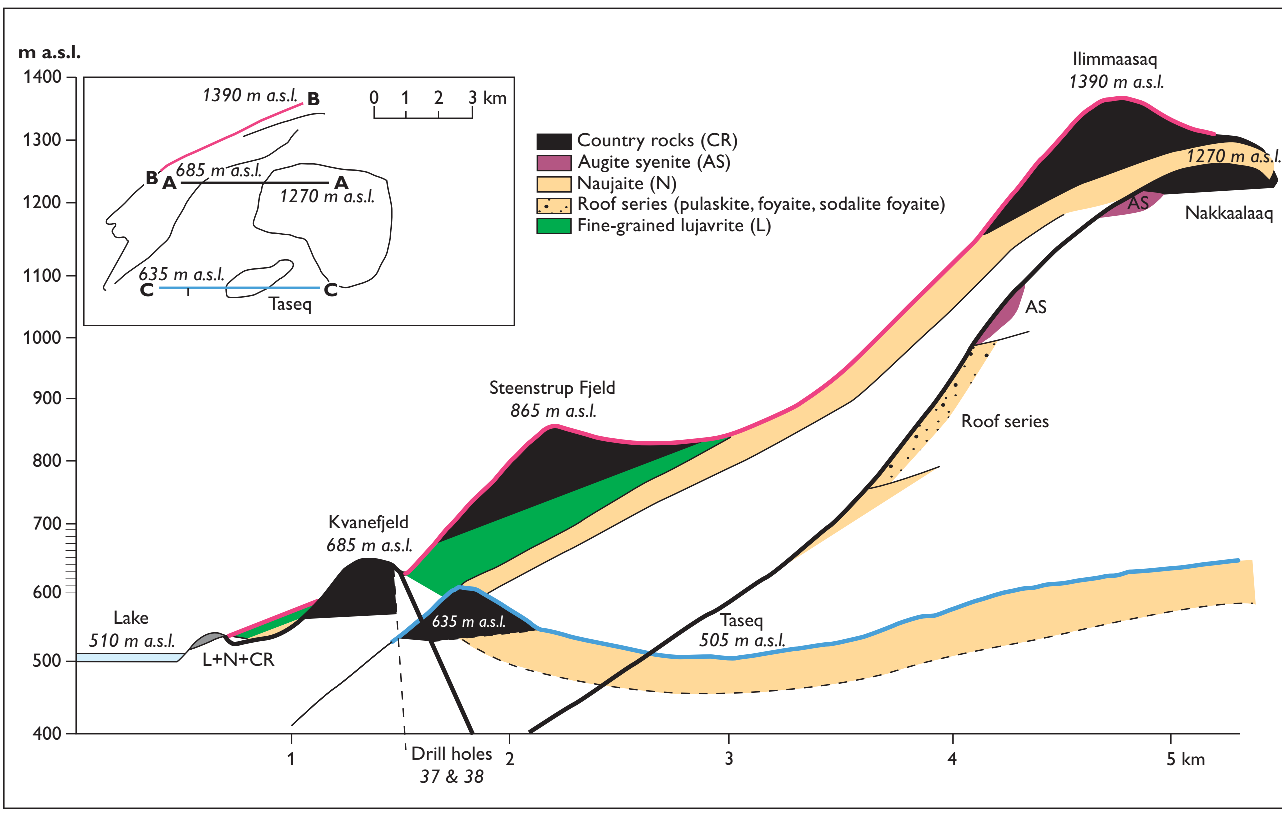


Fig. 8. Three vertical cross sections of the Narsaq Elv valley based on the geological map of Ferguson (1964). The black section (AA) runs from the roof remnant at 1270 m in the Nakkaalaaq mountain over the Kvanefjeld peak (685 m) to lake 510 m (517 m in Fig. 2) at the northern contact of the Ilímaussaq complex. This section intersects the volcanic roof rocks, augite syenite (alkali granite is omitted), and the roof series dominated by sodalite foyaite and naujaite. The red section (BB) runs from the Ilimmaasaq mountain (1390 m) over Steenstrup Fjeld (865 m) to lake 510 m at the northern contact of the complex and shows the contact between the volcanic country rocks and naujaite, and from 800 m a.s.l. between a lujavrite and the country rocks. The blue section (CC) passes through the Taseq lake (505 m) and the peak 635 m. The blue and red sections show the contact between naujaite and the volcanic country rocks (*cf*. Fig.9).

At the Kvanefjeld plateau, naujaite xenoliths are generally separated from the country rocks by lujavrite, but direct contact exists in a number of cores in the northernmost part of the plateau. One would expect to find sodalite foyaite, foyaite and pulaskite between the naujaite and the overlying country rocks and this is actually the case in core 48. The occurrence of pulaskite, foyaite and sodalite foyaite is, however, restricted to the apical part of the naujaite, whereas naujaite is in direct contact with the country rocks at the lateral contacts (Sørensen 2006).

Xenoliths of sodalite foyaite, foyaite and pulaskite in the lujavrites in the northernmost parts of the Kvanefjeld plateau and the Steenstrup Fjeld area show that the lujavrite magma at least locally penetrated the apical part of the naujaite and came into contact with the overlying rocks. These xenoliths are interpreted as remnants of a westward plunging extension of the package of earlier rocks that overlies the naujaite at Nakkaalaaq (Sørensen 2006). The slope of the package is almost identical with the slopes of the north and west contacts of the naujaite against the country rocks (Figs. 8, 9).

The augite syenite xenoliths in the south-western part of the Kvanefjeld plateau are intersected by deformation zones and intruded by lujavrite (Fig. 2). The observation of Nielsen and Steenfelt (1979) that an identical orientation of structures is seen in neighbouring augite syenite xenoliths, and the fact that augite syenite is in direct contact with the volcanic country rocks in the valley and Narsaq Elv river bed south of the Kvanefjeld plateau, show that most parts of the augite syenite have preserved their original position. The augite syenite in the river bed is intruded by naujaite and lujavrite (Ferguson 1964; Sørensen 2006). In this part of the complex, the lowest-lying contact between naujaite and the volcanic roof rocks is located in the Narsaq Elv bed, indicating that the augite syenite in the valley and the south-west slope of Kvanefjeld plateau formed an obstacle to the advance of the naujaite magma.

The two deepest boreholes, nos. 37 and 38 located in the southern part of the plateau, intersect gabbro and other roof rocks from respectively 560 to 260 and 670 to 330 m a.s.l. and roof rocks dominate a few of the shallow boreholes. The 960 m long tunnel intersects masses of roof rocks at 200-215, 450-588, 730-755 and 880-960 m from its opening. The locations of large masses of roof rocks at these deep levels may be parts of vertical screens of pre-naujaitic rocks that resisted successive attacks from intruding naujaitic and lujavritic magmas. They are intersected by thin sheets of augite syenite, more rarely by naujaite, but thicker sheets of arfvedsonite and naujakasite lujavrite have many small xenoliths of naujaite, suggesting that fissures in the screens were first invaded by naujaite and later by lujavrite.

The country rocks in the west contact of the complex are basalts intersected by a swarm of gabbroic dykes and, less than 1 km away, by the Dyrnæs-Narsaq intrusion consisting of gabbro, syenite and granite which is older than the Ilímaussaq complex (Allaart 1973). The massive gabbroic dykes, and perhaps also recrystallization caused by heat and emanations from

Fig. 9. Panorama of the Narsaq Elv valley looking upstream (north-east). The Ilimmaasaq mountain lies at the eastern end of the red section of Fig. 8. The blue section in Fig. 8 passes through peak 635 m and Kvanefjeld at 685 m, and the black section runs from highest part of the Nakkaalaaq mountain across the light grey slope of naujaite to Kvanefjeld. The dark walls on both sides of the Narsaq Elv valley are the volcanic rocks of the west contact of the Ilímaussaq complex.

the consolidating Dyrnæs-Narsaq complex, may have fortified the volcanic country rocks. The large roof xenoliths in the southern part of Kvanefjeld plateau consist of these resistant country rocks. The elevation of their underside is almost the same as that of the volcanic rocks in contact with the naujaite on the south side of the Narsaq Elv valley and fits exactly the extrapolation of the course of the contact between naujaite and the overlying volcanic roof rocks located north and south of Kvanefjeld plateau (Figs. 8, 9). This supports the view of Sørensen *et al.* (1974) that the large xenoliths of roof rocks that cover most of the southern part of Kvanefjeld plateau have retained their original position and are *in situ* remnants of the roof of the lujavrite magma.

Very few large country rock xenoliths are exposed in the northern part and the intermediate zone of the Kvanefjeld plateau, but up to 50 m thick xenoliths of the volcanic roof are common in the cores from these parts of the plateau. In our opinion, these xenoliths and the above-mentioned naujaite xenoliths are fragments of the rocks that constituted the roof of the intruding lujavrite magma.

The Steenstrup Fjeld lujavrites are continuous with the lujavrite of the northern Kvanefjeld plateau but their relation to the lujavrite in the south Kvanefjeld area is not visible because the rocks have been eroded between the Steenstrup Fjeld area and the escarpment that forms the south-east margin of Kvanefjeld plateau (Fig. 3). Thin veins of lujavrite in fractures in the large roof xenolith that forms the escarpment may, however, be an incipient penetration of lujavrite magma.

Larsen (1977) demonstrated that the lava sequences in the Kvanefjeld xenoliths are located 300–400 m lower than identical lavas in the undisturbed lava sequence outside the complex. This would support the idea that a foundering of large masses of roof rocks took place in connection with the emplacement of the lujavrite. Against this idea speaks, firstly, that the the volcanic roof rocks and naujaite of the Kvanefjeld plateau are located at the same elevation as the same rocks on the south side of the Narsaq Elv valley, and, secondly, that the regular course of the contact between naujaite and the country rocks (Figs. 8, 9) suggests that displacement of the lava sequences took place before emplacement of the naujaite. Fault activity was most probably the cause of major displacement of the country rocks before emplacement of the Ilímaussaq complex (Sørensen 2006).

Nielsen & Steenfelt (1979) pointed out that pulaskite belongs to a higher stratigraphic level in the complex than naujaite. Therefore, the occurrence of pulaskite xenoliths at Kvanefjeld at the same level as the naujaite and marginal pegmatite of the contact should indicate that the pulaskite xenoliths have foundered in the lujavrite melt. Sørensen (2006) argued that the occurrence of the whole suite of the roof series rocks from pulaskite to sodalite foyaite in one xenolith means that the roof series here was very thin and that the pulaskite xenoliths may therefore be more or less in their original position.

Naujakasite lujavrite

Naujakasite ($Na_6(Fe,Mn)Al_4Si_8O_{26}$) is a unique mineral. It is composed of common elements and is a rock-forming mineral in the Ilímaussaq complex where it constitutes up to 80 % of the naujakasite lujavrite. However, the Ilímaussaq complex is the only place in the world where it has been found. This must mean that its stability field is very restricted or unique. Khomyakov *et al.* (2001) conclude that naujakasite is formed in hyperagpaitic magmas rich in Fe and Mn and with a high Na/K ratio, and emphasize the frequent occurrence beneath large xenoliths of naujaite, augite syenite and volcanic country rocks, i.e. places where volatiles could accumulate. Andersen & Sørensen (2005) consider that an uncommon combination of low oxygen fugacity and high water activity stabilises naujakasite in highly sodic liquids.

Naujakasite lujavrite forms the upper part of arfvedsonite lujavrite sequences beneath large xenoliths of naujaite, augite syenite and volcanic country rocks, but there is commonly a thin naujakasite-free zone of arfvedsonite lujavrite between the xenolith and the underlying naujakasite lujavrite. The alternation of layers with and without naujakasite shows that the stability field of naujakasite is narrow, whereas the large masses of naujakasite lujavrite indicate that the stability field can be attained in large masses of magma at the same time.

Naujakasite lujavrite occurs at several levels in the south Kvanefjeld area and the intermediate zone (Figs. 5, 6C). The highest-lying naujakasite lujavrites have most probably been in contact with the rocks which formed the roof over the lujavrite magma and at lower elevations with naujaite and augite syenite xenoliths.

Naujakasite lujavrite is absent in most cores from the contact-near Kvanefjeld-Steenstrup Fjeld lujavrite belt and has only been observed in three cores (39, 50 and 70). These lujavrites are situated at a higher elevation than all other lujavrite cores of the plateau. The U contents increase upwards in the arfvedsonite lujavrites in these cores, and the specific conditions required to stabilize naujakasite were only met in their upper parts. Gamma-spectrometric logging shows that in arfvedsonite lujavrite sequences crystallizing close to the roof of the magma, U contents generally increase upwards, often paralleled by Th contents, but remain more or less constant throughout the naujakasite lujavrites (Sørensen *et al.* 1971; Nyegaard *et al.* 1977). This can be explained by the narrow stability field of naujakasite. Some of these sequences terminate upwards in a naujakasite-free arfvedsonite lujavrite which generally has lower U contents and higher Th contents than the underlying rock. The upwards decrease in U could in fact be a downward increase, if the conditions for crystallization of naujakasite were established some time after the lujavrite magma came in contact with the overlying xenolith.

Outside the Kvanefjeld plateau, naujakasite lujavrite occurs in the uppermost part of the arfvedsonite lujavrites south of Tupersuatsiaat bay on the south coast of Tunulliarfik Fjord (Fig. 1; Bondam & Sørensen 1958; Petersen & Andersen 1975; Khomyakov *et al.* 2001) and in the uppermost part of the lujavrites underlying the naujaite south, east and west of Tupersuatsiaat (Danø & Sørensen 1959). Naujakasite lujavrite also occurs as dykes in the naujaite north of the Taseq lake (Engell 1973). This emphasizes that the presence of a lid of strong country rocks which prevents volatile and residual elements from escaping is a pre-condition for crystallization of naujakasite and steenstrupine in lujavrite magmas and for the formation of the Kvanefjeld type of U–Th–REE deposits.

The importance of this condition is demonstrated by the upward increasing contents of U, REE and Y in the upper parts of six of the drill holes located 6 km south of Kvanefjeld (GMEL 2011). These drill holes intersect the dome of the central arfvedsonite lujavrite body. This dome passes westwards into a depression of the upper surface of the lujavrite above the site of borehole II on the north coast of Tunulliarfik (Fig. 1). The uppermost 70 m of the lujavrite here are rich in steenstrupine and have up to 1200 ppm U and 5500 ppm Th (Sørensen 1962; Rose-Hansen & Sørensen 2002).

Magmatic evolution of the fine-grained Kvanefjeld lujavrites

The 4.5 km long lujavrite belt from Ilimmaasaq mountain to the Kvanefjeld plateau separates naujaite, the dominating agpaitic rock of the upper part of the Ilímaussaq complex, from its supracrustal country rocks along a NE–SW oriented part of the north contact and in the north-western corner of the complex. It is interpreted to be an offshoot from the sandwich horizon lujavrite magma in the central part of the complex. On the Kvanefjeld plateau, a northern and a southern lujavrite facies may be distinguished. The northern facies forms a continuous belt from the foothills of Ilimmaasaq mountain in the east to the west contact of the complex (Fig. 1) and is dominated by ordinary arfvedsonite and aegirine lujavrites. The southern facies occurs in the southern part of the Kvanefjeld plateau and in the intermediate zone where hyperagpaitic lujavrite varieties containing naujakasite, villiaumite and steenstrupine are widespread.

Nyegaard (1979) concluded that the lujavrites located near the north contact and in the Steenstrup Fjeld area were formed by a single pulse of relatively volatile-poor magma of deep origin, whereas the lujavrites in the central part of the plateau were formed by several pulses of lujavrite magma from a relatively high level in the central lujavrite magma chamber. We have observed no major discontinuities but cannot exclude their existence between the exposed lujavrites and those covered by roof xenoliths, i.e. caused by vertical screens of country rocks. Gradational vertical relations are, however, observed in drill cores.

The general stratigraphy of the lujavrite sandwich in the central part of the complex was assembled over several studies (Ferguson 1964; Andersen *et al.* 1981a, b; Bohse & Andersen 1981; Sørensen 2006; Sørensen *et al.* 2006). The lowermost part consists of aegirine lujavrite which is overlain by a sequence of alternating aegirine and arfvedsonite lujavrite followed by the main mass of arfvedsonite lujavrite. It is interesting that the sequence of crystallization of the main lujavrite sandwich is largely repeated at Kvanefjeld. A large xenolith of aegirine lujavrite in the gully between the Ilimmaasaq mountain and Steenstrup Fjeld is proof of the former existence of aegirine lujavrite at this place. Aegirine is common in the contact-near arfvedsonite lujavrites and in arfvedsonite lujavrite in contact with naujaite xenoliths. The marginal lujavrites along the north contact have layered sequences and horizons of spheroidal lujavrites, and similar rocks are seen to lie immediately above the aegirine lujavrite on the north coast of Tunulliarfik and at Appat south of Tunulliarfik (Sørensen *et al.* 2003; Sørensen 2006) , i.e. the Kvanefjeld magma appears to stem from the lower part of the arfvedsonite lujavrite sandwich.

The Kvanefjeld lujavrites follow the Zr-U-Y geochemical trend found among lujavrites in the southern Ilímaussaq complex but evolve to even lower values of Zr, Zr/U and Zr/Y and higher values of U and Y, especially in the naujakasite lujavrite (Andersen *et al.* 1981a). These trends were attributed to fractionation of eudialyte. The Kvanefjeld lujavrites were thought to have undergone more prolonged fractionation in an isolated magma chamber, an evolution that eventually led to naujakasite lujavrite, the most fractionated of the Kvanefjeld lujavrites.

Andersen *et al.* (1981a) also noted that the Zr-U data from kakortokites plot along well-defined correlation lines whereas the Zr-U data from the Kvanefjeld lujavrites tend to plot in fields or clusters. They attributed this to the changing character of the analysed rocks.

Thus, the kakortokites represent well-layered cumulate rocks which resulted from efficient density sorting of cumulus minerals into black, red and white layers. In contrast, in the overlying lujavrites, the decreased vertical interval for crystal settling and the mush-like character of the magmas led to poor separation of cumulus phases from the magma. Overall, the combination of rapid fractionation and the appearance of poorly sorted partial cumulates led to the samples plotting in fields or clusters on geochemical diagrams.

Kunzendorf *et al.* (1982) considered that the Kvanefjeld lujavrites crystallized from bottom to top and that fractionation of eudialyte crystals by gravity settling gave rise to increasing U and Th contents in the highest levels, as had been documented by Nyegaard *et al.* (1977). Fractionation of eudialyte took place in the early aegirine lujavrite stage of the central sandwich lujavrites (Andersen *et al.* 1981a, b). Enrichment in eudialyte has been demonstrated in the light-coloured layers in micro-layered arfvedsonite lujavrites on the north coast of Tunulliarfik, but the much thicker dark-coloured layers are poor in eudialyte and there is no general fractionation of eudialyte upwards in the lujavrite sequence (Bailey *et al.* 2006). Our petrographic studies indicate that the fractionation effect of eudialyte was minimal or non-existent after the early arfvedsonite lujavrite and that there are no signs of crystal fractionation in the scale needed to explain the exceptionally high contents of F, P, Na, REE, Th, U etc. in the Kvanefjeld lujavrites.

Larsen & Sørensen (1987) and Sørensen & Larsen (1987) emphasized that the kakortokite-lujavrite suite behaved as a multiply saturated (anchieutectic) system with feldspars, nepheline, aegirine, arfvedsonite, eudialyte and occasionally sodalite as liquidus phases. Crystallization took place in a stagnant bottom layer of the magma and released residual liquids to the overlying magma, which would crystallize the liquidus assemblage releasing volatile and residual elements to the overlying magma, and so on. This resulted in the rather constant composition of rocks and minerals in the kakortokites (*cf.* Sørensen & Larsen 1987 and Pfaff *et al.* 2008) and in the sandwich of arfvedsonite lujavrites (Rose-Hansen & Sørensen 2002). The rock-forming minerals incorporate traces of residual volatile elements, e.g. H_2O and F in arfvedsonite and U in eudialyte, and the U content of eudialyte shows a weak increase upwards in the layered sequence (Bohse *et al.* 1974). The accessory minerals britholite, vitusite, and monazite occur in so small amounts that U, Th, REE and P would steadily be squeezed out and move upwards as long as the system was closed. Thus liquid fractionation, rather than crystal fractionation, was involved in the formation of the Kvanefjeld deposit.

According to Greenland Minerals and Energy Ltd., the mass of the indicated and inferred U–REE–Zn multielement occurrence at Kvanefjeld is 457 million tons. The volume of 457 million tons of lujavrite is about 0.16 billion cubic kilometres, corresponding to a body measuring 1000×1000×160 m, which is the right order of magnitude. The uranium resource is 283 M lbs U_3O_8 (i.e. about 110,000 t of U) at a cut-off grade of 150 ppm and an average grade of 280 ppm U_3O_8 or 240 ppm U (GMEL 2011). The lowermost arfvedsonite lujavrites of the central sandwich lujavrite body have 40–100 ppm U (Rose-Hansen & Sørensen 2002). If we assume that the uranium content of the original lujavrite magma was 50 ppm, 100,000 tons of uranium corresponds to the total quantity of U in 2.2 billion tons or 0.8 cubic kilometres of original arfvedsonite lujavrite magma. The Kvanefjeld-Ilimmaasaq lujavrite belt is about 4.5 km long and its dyke (northern) facies is about 300 m wide. A volume of 0.8 cubic kilometres of lujavrite magma emplaced in a fracture of this size would be about 500 m deep, corresponding to a derivation at a low level in the lujavrite sandwich horizon. The figure for the uranium resource includes the U contained in the arfvedsonite M-C lujavrite and its contact aureole estimated to 14,420 t by Sørensen *et al.* (1974).

Comparison of the mass of the Kvanefjeld ore body with that of the assumed original lujavrite magma indicates that the formation of the ore body requires crystallization of about 80% of the original lujavrite magma.

Comparison with the central arfvedsonite lujavrite body

Twelve boreholes located approximately 6 km south and south-east of Kvanefjeld (GMEL, 2011) provide new information about the main mass of the central sandwich of arfvedsonite lujavrite. Six of these boreholes intersect the marginal part and six the central part of the dome-shaped contact between the naujaite and the underlying lujavrite which is exposed in the north wall of Tunulliarfik (Fig. 10). The lujavrites of the marginal cores and the lower part of the central cores display the uniform contents of U, REE and Y which we, as discussed above, ascribe to the anchieutectic crystallization of the sandwich arfvedsonite lujavrite magma and the continuous release of incompatible elements to the overlying magma. The contents of U, REE and Y in the marginal facies are similar to those in the lower part of the sandwich lujavrite sequence. In the upper 100–200 m of the six central cores, the contents of U, REE and Y increase upwards until 20–50 m from the roof of the magma chamber from where the contents decrease upwards. (In some cores, the LREE contents continue to increase upwards).

The higher contents of U, REE and Y in the upper than in the lower central lujavrites may be explained as follows. When the ascending central lujavrite magma met the impervious roof of the magma chamber, the release of volatile and residual elements to the overlying magma was prevented. The elevated contents of residual and volatile elements in the lujavrite magma stored under the roof caused a lowering of its liquidus temperature and its density. Eventually, the magma crystallized from the roof downwards and from its base upwards, the uppermost 30–50 m of lujavrites displaying a downward increase in U contents and the lower part an upwards increase resulting in the formation of steenstrupine lujavrite. The upper part may be termed an 'upper border group' of lujavrite.

The average U content of the central lujavrites is higher than that of the Kvanefjeld lujavrites. This can be related to the much larger volume of lujavrite magma in the central part of the intrusion and suggests that this sequence of arfvedsonite lujavrites consolidated beneath a roof that prevented volatiles from escaping during the major part of crystallization. This view is strengthened by the presence of an upper border group, i.e. a contact facies of this part of the lujavrite body. Further evidence of the importance of a volatile phase is found in sheets and dykes of steenstrupine arfvedsonite lujavrite and naujakasite lujavrite and widespread albite veins rich in Be minerals intersecting the overlying naujaite, indicating fracturing of the naujaite roof at a late stage in the consolidation of the main arfvedsonite lujavrite intrusion (Engell *et al*. 1971; Engell 1973).

The emplacement mechanism of the Kvanefjeld lujavrites

The Kvanefjeld plateau is the broadest part of the Kvanefjeld - Ilimmaasaq lujavrite belt. The contact between the country rocks and the lujavrites in the foothills of the Steenstrup Fjeldand Ilimmaasaq mountains and in the northern part of the Kvanefjeld plateau is NE–SW oriented, vertical, unbroken and practically straight. The widening of the lujavrite belt was therefore towards the south. The lujavrites there have higher contents of U, Th and REE than those in the narrower part of the belt east of the plateau. It is therefore of interest to know the cause of the widening. Three explanations may be proposed:

1. The intruding lujavrite spread out when it encountered the solid mass of volcanic rocks, gabbro, naujaite, etc. which then occupied the Kvanefjeld area. It invaded fractures in these rocks, engulfing xenoliths of these, and penetrated the western contact forming the three lujavrite fingers that petered out after about 1 km (Fig. 1). There are, however, no indications of spreading in the lujavrites in the Steenstrup Fjeld area and it is difficult to see how the evolved lujavrites in the south Kvanefjeld area could be formed from the less evolved magma disseminated in small volumes across the plateau.

2. Our favoured explanation is that the intruding Kvanefjeld lujavrite magma was forcefully injected in a fracture system along the north contact of the complex from Ilimmaasaq mountain to the northwestern corner of the complex (Figs. 3, 4). The magma was bounded to the north and west and at its roof by the dyke-enforced country rocks which arrested its advance. The southwest and south walls of the confined magma consisted of augite syenite, naujaite and overlying roof rocks. The multiply saturated lujavrite magma stored in the fracture crystallized from the bottom upwards, squeezing residual and volatile components upwards. Pressure would rise in the upper part of the magma. We imagine that when the pressure exceeded the strength of the weakest confining rocks, i.e. naujaite and augite syenite in the west and southwest walls, a violent explosion opened fractures in these rocks. The north wall and the roof of the fracture did not yield and reflected the north-directed pressure waves to reinforce the south-directed pressure, squeezing the volatile-rich

Fig. 10. The north wall of Tunulliarfik showing the dome shape of the central lujavrite (dark grey, the upper boundary marked with a dashed white line) and the lujavrite off-shoots in the overlying naujaite (at arrows). Note the horizons of naujaite rafts (white) in the dark lujavrite.

magma into fractures in not only naujaite and augite syenite but also in the overlying volcanic roof rocks where it consolidated as sheets of steenstrupine arfvedsonite lujavrite accompanied by mineralizations of steenstrupine, Li-mica, sphalerite, Be-minerals and monazite formed from the released volatile phase. Xenoliths of pulaskite, foyaite and sodalite foyaite in the lujavrites indicate that the apical part of the Ilímaussaq complex was penetrated by the lujavrite magma. The violence of the process is demonstrated by a) the widening of the plateau towards the south, b) the three NE–SW oriented lujavrite fingers that penetrated the south-west wall in prolongation of the fracture system through which the lujavrite was emplaced (Fig. 1), c) the small xenoliths of roof and wall rocks, especially volcanic rocks and naujaite, that are widely distributed in the lujavrites, d) the occurrence of xenoliths of higher-lying rocks such as pulaskite and sodalite foyaite in lujavrite veins that infiltrate the low-lying deformed masses of augite syenite, syenite and anorthosite in a very intricate way (Nielsen & Steenfelt 1979; Sørensen 2006) and e) the strong deformation and recrystallization of country rocks adjacent to near-horizontal fractures in these in the depth interval 650 to 450 m a.s.l. in almost all drill cores from the southern part of the plateau; such a mineralised fracture was described by Sørensen *et al*. (1974, p. 35), and the adjacent roof rocks are strongly sheared, deformed and recrystallized but they are perfectly fresh a few metres from the fracture. The explosive squeezing-out of the volatile-rich lujavrite magma that occupied the upper part of the fracture made room for volatile-poor magma from the lower part of the fracture, which crystallized to form the lujavrites in the north Kvanefjeld–Ilimmaasaq lujavrite belt.

3. A third cause of widening of the lujavrite belt and the elevated contents of U, Th, REE, etc. could be that this is the place where the lujavrite magma ascended from the underlying sandwich lujavrite magma.

Some evidence may be gleaned from the central arfvedsonite lujavrite body. Boreholes in the naujaite areas 3–7 km south and south-east of Kvanefjeld (Fig. 1) show that the naujaite is underlain by alternating lujavrite and naujaite horizons (GMEL 2008, 2011). A similar relationship between naujaite and the underlying sandwich lujavrite can be seen in the north wall of the Tunulliarfik fjord (Figs. 1, 10), and supports the view of Ussing (1912) and subsequent authors that the sandwich horizon lujavrite underlies naujaite in the whole complex. This view is strengthened by the occurrence of lujavrite dykes and sheets intersecting the naujaite north of the Taseq lake (Engell 1973), the Narsaq Elv bed and drill core I (Fig. 1) (Rose-Hansen & Sørensen 2002). In the north wall of Tunulliarfik, it is clearly seen that such veins are offshoots from the sandwich horizon (Figs. 1, 10).

In the cross sections of the complex provided by the north and south coasts of Tunulliarfik, the upper surface of the lujavrite shows swells and depressions (Sørensen 2006). The Kvanefjeld – Steenstrup – Ilimmaasaq lujavrite belt may be a swell, the Narsaq Elv valley a depression and the Taseq area a swell.

Without knowing the distribution of rocks beneath the Kvanefjeld plateau it is impossible to decide whether the lujavrite magma was introduced along the north contact, from below the plateau, or both. In the first case, one would expect that the evolved lujavrites in horizontal fractures in the roof rocks are underlain by naujaite, in the last case by lujavrites or lujavrites with horizontal rafts of naujaite. Our deepest borehole (37) terminates with 30 m naujaite at 173 m a.s.l., which could support the first view.

The Kvanefjeld U-Th-REE deposit

It is a general observation that U, Th and REE are concentrated in the upper parts of the youngest components of igneous complexes. This is also the case in the Ilímaussaq complex where the uppermost part of the youngest phase, the lujavrite sandwich horizon, has higher contents of U, Th, LREE, Li, Be and Zn than the lower part, the kakortokites. These are rich in eudialyte and have high contents of Zr, Hf, HREE, Nb, Ba and Sr (Bailey *et al.* 1981).

Sørensen *et al.* (1974) distinguished six types of U–Th mineralization in drill cores 1–43 at Kvanefjeld: (1) arfvedsonite lujavrite with interstitial steenstrupine crystals, monazite, U-bearing pigmentation and pseudomorphs after eudialyte. The steenstrupine crystals are generally unaltered; (2) naujakasite lujavrite with interstitial steenstrupine crystals which may be enclosed in naujakasite and are generally more altered than in type 1; (3) lujavrites in which analcime replaces the felsic minerals and naujakasite. The steenstrupine is commonly poikilitic and strongly altered; (4) the contact metasomatic mineralization around the M-C lujavrite intrusion in the south Kvanefjeld area, which has the highest recorded contents of U and Th on the plateau; (5) similar but much smaller mineralizations associated with the aegirine– rich M-C lujavrite near the north contact; and (6) mineralization in zones of deformation in xenoliths enclosed in the lujavrite.

The chemical composition of the arfvedsonite lujavrites in the central sandwich horizon is rather monotonous, both horizontally and vertically. There is, however some variation in contents of U, Th, and REE due to xenoliths of country rocks and naujaite with low contents of these elements or to intersecting steenstrupine-bearing pegmatites and hydrothermal veins. It is therefore difficult to give precise values for average contents, but 100 ppm U, 100 ppm Th and 8,000 ppm REE are characteristic values for the main mass of arfvedsonite lujavrites. Higher contents are found in the Kvanefjeld area, in the highest-lying exposed lujavrites south of Tupersuatsiaat and on the north coast of Tunulliarfik.

In the earlier agpaitic rocks of the complex, REE are mainly held in eudialyte (Bailey *et al.* 2001), but the copious crystallization of eudialyte in kakortokite and early lujavrites led to decreased contents of Zr so that eudialyte became a minor mineral in the early arfvedsonite lujavrite of Kvanefjeld and is absent in the subsequent Kvanefjeld lujavrites. During differentiation of the agpaitic rocks, P_2O_5 contents rose from *c.* 0.01 wt. % to 0.19 wt. % in the average arfvedsonite lujavrite with even higher levels in Kvanefjeld lujavrites (0.25–0.31 wt. %, Table 3). The association of REE, Na and P became dominant in the Kvanefjeld lujavrites and led to complex REE mineral assemblages. These include apatite (Rønsbo 2008) and monazite/rhabdophane; other phosphates where Si may replace P (vitusite, Pekov *et al*. 1997); silicophosphates where P replaces Si (steenstrupine, britholite); and silicates containing independent phosphate molecules (vuonnemite) (Makovicky & Karup-Møller 1981; Rønsbo *et al.* 1983; Kalsbeek *et al.* 1990).

North of Tunulliarfik, a major part of the exposed rocks of the complex consists of naujaite, but since Ussing (1912) it has been the general opinion that the naujaite is underlain by arfvedsonite lujavrite. This led Sørensen (in IAEA 1980, p. 158) to suggest that the speculative resources in the Kvanefjeld area could amount to 600,000 t U at 150 ppm U, in addition to the 43,000 t reasonably assured and estimated additional resources known at that time. Sørensen (1992) argued that multi-element mining would be the way to exploit the rare elements of the arfvedsonite lujavrite.

Conclusions

The lujavrites along the northwestern margin of the Ilímaussaq complex constitute a 5 km long elongate intrusion of which the Kvanefjeld plateau is the western part. The intrusion was formed by consolidation of an off-shoot from the sandwich horizon of arfvedsonite lujavrite magma in the central Ilímaussaq magma chamber. Field relations suggest that the off-shoot was emplaced through a fracture zone along parts of the north contact of the complex, but we cannot exclude the possibility that there were other routes.

Two facies of fine-grained arfvedsonite lujavrites may be distinguished in the U–Th–REE deposit at Kvanefjeld. One facies comprises the continuous lujavrite belt in the northern part of the Kvanefjeld plateau which extends to the north-east below Steenstrup Fjeld. These lujavrites have contents of U, Th and REE that are lower than in most other lujavrites of the Kvanefjeld plateau, but slightly higher than in the arfvedsonite lujavrite sandwich in the central part of the complex. The second lujavrite facies comprises the fine-grained arfvedsonite lujavrites in the southern part of the Kvanefjeld plateau which consolidated under a strong roof of gabbro-reinforced volcanic rocks that make up most of the surface of this area and are interpreted as *in situ* remnants of the original roof of the lujavrite magma. In the intermediate zone and in the northern Kvanefjeld plateau the roof has been fragmented into separate large xenoliths.

The high contents of U, Th and REE in the lujavrite facies in the southern part of the Kvanefjeld plateau, and the evidence of a violent emplacement process, indicate that volatiles and residual elements assembled at the top of the crystallizing off-shoot magma pool leading to increasing pressure and an explosion that squeezed the volatile-rich magma into fractures in the western and southern sidewalls of the magma chamber where it consolidated as steenstrupine-rich arfvedsonite lujavrite.

The violent expulsion of the volatile-rich magma made room for magma with lower contents of volatile and residual elements which streamed in from below and crystallized in the feeder system through which the magma was emplaced.

The formation of the Kvanefjeld type of U–Th–REE deposit requires slow, uninterrupted crystallization of a large volume of an agpaitic magma enriched in residual and volatile elements below a tight cover. This is a rarely met combination of conditions which explains why the Ilímaussaq complex is the only known occurrence of large masses of hyperagpaitic rocks and that naujakasite and rock-forming steenstrupine are only known from this complex.

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